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Der Präsident des Europäischen Patentamts;
Im Auftrag

For the President of the European Patent Office

Le Président de l'Office européen des brevets
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Levelling Control in Lithographic Projection Apparatus

The present invention relates to the control of leveling, for example of the substrate and/or mask, during exposures in lithographic apparatus. More particularly, the invention relates to a system for leveling control in a lithographic projection apparatus comprising:

a radiation system for supplying a projection beam of radiation;

a first object table provided with a first object holder for holding a mask;

a second object table provided with a second object holder for holding a substrate;

a projection system for imaging an irradiated portion of the mask onto a target portion of the substrate;

a level sensor for measuring at least one of the vertical position and tilt about at least one horizontal axis of an object held by one of said object holders, and generating a position signal; and

a servo system responsive to said position signal for moving said object to a desired position.

For the sake of simplicity, the projection system may hereinafter be referred to as the "lens"; however, this term should be broadly interpreted as encompassing various types of projection system, including refractive optics, reflective optics, catadioptric systems, and charged particle optics, for example. The radiation system may also include elements operating according to any of these principles for directing, shaping or controlling the projection beam, and such elements may also be referred to below, collectively or singularly, as a "lens". In addition, the first and second object tables may be referred to as the "mask table" and the "substrate table", respectively.

In the present document, the terms "radiation" and "beam" are used to encompass all types of electromagnetic radiation or particle flux, including, but not limited to, ultraviolet radiation (e.g. at a wavelength of 365nm, 248nm, 193nm, 157nm or 126nm), extreme ultraviolet radiation (EUV), X-rays, electrons and ions. Also herein, the invention is described using a reference system of orthogonal X, Y and Z directions and rotation about an axis parallel to the Z direction is denoted R_z. Further, unless the context otherwise requires, the term "vertical" (Z) used herein is intended to refer to the direction normal to the substrate or mask surface, rather than implying any particular orientation of the apparatus. Similarly, the term

"horizontal" refers to a direction parallel to the substrate or mask surface, and thus normal to the "vertical" direction.

Lithographic projection apparatus can be used, for example, in the manufacture of integrated circuits (ICs). In such a case, the mask (reticle) may contain a circuit pattern corresponding to an individual layer of the IC, and this pattern can be imaged onto an exposure area (die) on a substrate (silicon wafer) which has been coated with a layer of photosensitive material (resist). In general, a single wafer will contain a whole network of adjacent dies which are successively irradiated via the reticle, one at a time. In one type of lithographic projection apparatus, each die is irradiated by exposing the entire reticle pattern onto the die in one go; such an apparatus is commonly referred to as a wafer stepper. In an alternative apparatus — which is commonly referred to as a step-and-scan apparatus — each die is irradiated by progressively scanning the reticle pattern under the projection beam in a given reference direction (the "scanning" direction) while synchronously scanning the wafer table parallel or anti-parallel to this direction; since, in general, the projection system will have a magnification factor M (generally < 1), the speed V at which the wafer table is scanned will be a factor M times that at which the reticle table is scanned. More information with regard to lithographic devices as here described can be gleaned from International Patent Application WO97/33205, for example.

Until very recently, lithographic apparatus contained a single mask table and a single substrate table. However, machines are now becoming available in which there are at least two independently moveable substrate tables; see, for example, the multi-stage apparatus described in International Patent Applications WO98/28665 and WO98/40791. The basic operating principle behind such multi-stage apparatus is that, while a first substrate table is at the exposure position underneath the projection system for exposure of a first substrate located on that table, a second substrate table can run to a loading position, discharge a previously exposed substrate, pick up a new substrate, perform some initial measurements on the new substrate and then stand ready to transfer the new substrate to the exposure position underneath the projection system as soon as exposure of the first substrate is completed; the cycle then repeats. In this manner it is possible to increase substantially the machine throughput, which in turn improves the cost of ownership of the machine. It should be understood that the same principle could be used with just one substrate table which is moved between exposure and measurement positions.

During exposure processes, it is important to ensure that the mask image is correctly focussed on the wafer. Conventionally this has been done by measuring the vertical position of

the best focal plane of the aerial image of the mask relative to the projection lens before an exposure or a series of exposures. During each exposure, the vertical position of the upper surface of the wafer relative to the projection lens is measured and the position of the wafer table is adjusted so that the wafer surface lies in the best focal plane. However, known leveling systems have not always been able to effect sufficiently accurate positioning of the wafer surface in the best focal plane and can cause undesirable X and Y movements of the wafer due to crosstalk from Rx and Ry leveling adjustments. Such X and Y movements cause overlay errors which are particularly undesirable.

An object of the present invention is to provide a control system capable of improved "on-the-fly" leveling (that is leveling based on position measurements made during the exposure rather than in advance) performed on a substrate or mask in a lithographic projection apparatus during exposure processes and in particular to reduce focussing errors, crosstalk between tilts and horizontal shifts and unnecessary object table movements.

According to the present invention there is provided a lithographic projection apparatus comprising:

a radiation system for supplying a projection beam of radiation;

a first object table provided with a first object holder for holding a mask;

a second object table provided with a second object holder for holding a substrate;

a projection system for imaging an irradiated portion of the mask onto a target portion of the substrate;

a level sensor for measuring at least one of the vertical position and tilt about at least one horizontal axis of an object held by one of said object holders, and generating a position signal; and

a servo system responsive to said position signal for moving said object to a desired position; characterized by:

a filter connected between said level sensor and said servo system for filtering said position signal.

The present invention, by interposing a filter between the level sensor and the servo system for leveling, enables improvements in the leveling performance. In particular, undesirable movements to follow high spatial frequency variations in the wafer surface can be avoided. Also, trade-offs between performance in different degrees of freedom can be made, especially to avoid crosstalk into horizontal displacements of the wafer which would result in

overlay errors. Preferably, the level sensor, optionally in cooperation with a position sensor such as an interferometer or a Linear Variable Differential Transformer (LVDT) measurement system, generates a setpoint which the servo system aims to follow. The filter then filters that setpoint.

According to a further aspect of the present invention there is provided a method of manufacturing a device using a lithographic projection apparatus comprising:

a radiation system for supplying a projection beam of radiation;

a first object table provided with a mask holder for holding a mask;

a second object table provided with a substrate holder for holding a substrate;

a level sensor for measuring at least one of the vertical position and tilt about at least one horizontal axis of an object held by one of said object holders, and generating a position signal; and

a servo system responsive to said position signal for moving said object to a desired position; the method comprising the steps of:

providing a mask bearing a pattern to said first object table;

providing a substrate having a radiation-sensitive layer to said second object table; and

imaging said irradiated portions of the mask onto said target portions of the substrate whilst operating said servo system to maintain said object at said desired position; characterized by the step of:

filtering said position signal before it is used by said servo system to control the position of said object.

In a manufacturing process using a lithographic projection apparatus according to the invention a pattern in a mask is imaged onto a substrate which is at least partially covered by a layer of energy-sensitive material (resist). Prior to this imaging step, the substrate may undergo various procedures, such as priming, resist coating and a soft bake. After exposure, the substrate may be subjected to other procedures, such as a post-exposure bake (PEB), development, a hard bake and measurement/inspection of the imaged features. This array of procedures is used as a basis to pattern an individual layer of a device, e.g. an IC. Such a patterned layer may then undergo various processes such as etching, ion-implantation (doping), metallization, oxidation, chemo-mechanical polishing, etc., all intended to finish off an individual layer. If several layers are required, then the whole procedure, or a variant thereof, will have to be repeated for each new layer. Eventually, an array of devices (dies) will be present on the substrate (wafer). These devices are then separated from one another by a technique such as dicing or sawing, whence the individual devices can be mounted on a carrier,

connected to pins, etc. Further information regarding such processes can be obtained, for example, from the book "Microchip Fabrication: A Practical Guide to Semiconductor Processing", Third Edition, by Peter van Zant, McGraw Hill Publishing Co., 1997, ISBN 0-07-067250-4.

Although specific reference may be made in this text to the use of the apparatus according to the invention in the manufacture of ICs, it should be explicitly understood that such an apparatus has many other possible applications. For example, it may be employed in the manufacture of integrated optical systems, guidance and detection patterns for magnetic domain memories, liquid-crystal display panels, thin-film magnetic heads, etc. The skilled artisan will appreciate that, in the context of such alternative applications, any use of the terms "reticle", "wafer" or "die" in this text should be considered as being replaced by the more general terms "mask", "substrate" and "exposure area", respectively.

The present invention will be described below with reference to exemplary embodiments and the accompanying schematic drawings, in which:

Figure 1 depicts a lithographic projection apparatus according to a first embodiment of the invention;

Figure 2 depicts a level sensor device used in the first embodiment of the invention;

Figure 3 is a diagram of a control system used in the first embodiment of the invention;

Figure 4 is a diagram used to explain measurements used in a second embodiment of the invention;

Figure 5 is a diagram of a control system used in a second embodiment of the invention;

Figure 6 is a diagram showing the relative positions of measurement spots used in a third embodiment of the invention;

Figure 7 is a diagram of a control system used in the third embodiment of the invention;

Figure 8 is a diagram of a control system used in a fourth embodiment of the invention;

Figure 9 is a diagram of a control system used in a fifth embodiment of the invention;

Figure 10 is a diagram of a control system used in a sixth embodiment of the invention;

Figures 11A and B are graphs showing Z positions of a wafer stage during scanning of a test wafer with a conventional apparatus and with an apparatus embodying the invention;

Figures 12A and B are graphs showing Ry positions of a wafer stage during scanning of a test wafer with a conventional apparatus and with an apparatus embodying the invention;

Figures 13A and B are graphs showing Z position level sensor transfer functions of a conventional level sensor and a level sensor with filtering according to the invention, in each case compared to an ideal level sensor;

Figures 14A and B are graphs showing Ry position level sensor transfer functions of a conventional level sensor and a level sensor with filtering according to the invention, in each case compared to an ideal level sensor; and

Figure 15 is a table of wafershape filter settings in two examples of the invention.

In the drawings, like references indicate like parts.

Embodiment 1

Figure 1 schematically depicts a lithographic projection apparatus according to the invention. The apparatus comprises:

- a radiation system LA, Ex, IN, CO for supplying a projection beam PB of radiation (e.g. UV or EUV radiation);
- a first object table (mask table) MT provided with a mask holder for holding a mask MA (e.g. a reticle), and connected to first positioning means for accurately positioning the mask with respect to item PL;
- a second object table (substrate or wafer table) WT provided with a substrate holder for holding a substrate W (e.g. a resist-coated silicon wafer), and connected to second positioning means for accurately positioning the substrate with respect to item PL;
- a projection system ("lens") PL (e.g. a refractive or catadioptric system, a mirror group or an array of field deflectors) for imaging an irradiated portion of the mask MA onto an exposure area C (die) of a substrate W held in the substrate table WT.

As here depicted, the apparatus is of a transmissive type (i.e. has a transmissive mask). However, in general, it may also be of a reflective type, for example.

The radiation system comprises a source LA (e.g. a Hg lamp, excimer laser, an undulator provided around the path of an electron beam in a storage ring or synchrotron, a laser plasma source or an electron or ion beam source) which produces a beam of radiation. This beam is passed along various optical components comprised in the illumination system — e.g.

beam shaping optics Ex, an integrator IN and a condenser CO— so that the resultant beam PB has a desired shape and intensity distribution in its cross-section.

The beam PB subsequently intercepts the mask MA which is held in a mask holder on a mask table MT. Having passed through the mask MA, the beam PB passes through the lens PL, which focuses the beam PB onto an exposure area C of the substrate W. With the aid of the interferometric displacement and measuring means IF, the substrate table WT can be moved accurately by the second positioning means, e.g. so as to position different exposure areas C in the path of the beam PB. Similarly, the first positioning means can be used to accurately position the mask MA with respect to the path of the beam PB, e.g. after mechanical retrieval of the mask MA from a mask library or during a scan. In general, movement of the object tables MT, WT will be realized with the aid of a long-stroke module (course positioning) and a short-stroke module (fine positioning), which are not explicitly depicted in Figure 1. In the case of a waferstepper (as opposed to a step-and-scan apparatus) the reticle table may be connected only to a short-stroke positioning device, to make fine adjustments in mask orientation and position; or the reticle table may be fixed.

The depicted apparatus can be used in two different modes:

1. In step-and-repeat (step) mode, the mask table MT is kept essentially stationary, and an entire mask image is projected in one go (i.e. a single "flash") onto an exposure area C. The substrate table WT is then shifted in the X and/or Y directions so that a different exposure area C can be irradiated by the beam PB;

2. In step-and-scan (scan) mode, essentially the same scenario applies, except that a given exposure area C is not exposed in a single "flash". Instead, the mask table MT is movable in a given direction (the so-called "scan direction", e.g. the Y direction) with a speed v, so that the projection beam PB is caused to scan over a mask image; concurrently, the substrate table WT is moved in the same or opposite direction at a speed $V = Mv$, in which M is the magnification of the lens PL (typically, $M = 1/4$ or $1/5$). In this manner, a relatively large exposure area C can be exposed, without having to compromise on resolution.

An important factor influencing the imaging quality of a lithographic apparatus is the accuracy with which the mask image is focused on the substrate. In practice, since the scope for adjusting the position of the focal plane of the projection system PL is limited and the depth of focus of that system is small, this means that the exposure area of the wafer (substrate) must be positioned precisely in the focal plane of the projection system PL. To do this, it is of course necessary to know both the position of the focal plane of the projection system PL and the position of the top surface of the wafer. Wafers are polished to a very high degree of

flatness but nevertheless deviation of the wafer surface from perfect flatness (referred to as "unflatness") of sufficient magnitude noticeably to affect focus accuracy can occur. Unflatness may be caused, for example, by variations in wafer thickness, distortion of the shape of the wafer or contaminants on the wafer holder. The presence of structures due to previous process steps also significantly affects the wafer height (flatness). In the present invention, the cause of unflatness is largely irrelevant; only the height of the top surface of the wafer is considered. Unless the context otherwise requires, references below to "the wafer surface" refer to the top surface of the wafer onto which will be projected the mask image.

During exposures, the position and orientation of the wafer surface relative to the projection optics PL are measured and the vertical position (Z) and horizontal tilts (Rx, Ry) of the wafer table WT are adjusted to keep the wafer surface at the optimal focus position. The detector, referred to herein as the level sensor, used for this is shown in Figure 2. It comprises a radiation source S which has two emitting areas S1, S2 and supplies two beams, a reference beam and a measurement beam having a wide wavelength band. Also shown are an object grating G1 and an image grating G2. Optical systems (depicted for clarity as simple lenses) L1 and L2 image the object grating G1 onto the image grating G2, the reference beam having been reflected by the outer surface RP of the projection optics PL and the measurement beam by the wafer surface. Detectors DE2, DE1 behind the image grating G2 give signals, which can be measured by a meter ME or other suitable instrument, indicative of the relative positions of the points where the reference beam and measurement beam are reflected by the projection optics PL and wafer surface respectively. By using more than one such system, e.g. four, the relative heights of a corresponding number of points on the wafer surface can be measured and local tilts of the wafer surface determined. The level sensor is described in greater detail in EP-0 502 583-A and US 5,191,200 (P-0039), for example, which documents are incorporated herein by reference.

A schematic of the leveling control system is shown in Figure 3. The physical components of the system are the level sensor LS, wafershape filter WSF and servo system SV. The servo system SV is a closed loop system, including necessary control circuitry, a mechanism for driving the wafer table and a positioning system. The level sensor output *ls* filtered by the wafer shape filter WSF to give a filtered signal *ls'* which forms the setpoint of the servo system. The servo system drives the wafer table WT to a vertical position *vp* and may introduce a horizontal servo error *hse* in the horizontal position of the wafer. Such an error can be caused by a non-zero Abbe arm for the Rx and Ry rotations carried out by the servo system, for example. In other words, the servo system rotates the wafer table about axes not lying

exactly on the wafer surface. Any error *vse* in the vertical position signals output by the servo system SV can be measured by subtracting the filtered level sensor signal *ls'* from the measured vertical position *vp*. These components and their interconnections are shown in solid in Figure 3. It should be noted that leveling of the wafer is carried out in three degrees of freedom; vertical (Z) position and rotation about orthogonal horizontal axes (Rx and Ry). Figure 3, and later Figures showing other embodiments of the invention, show general control architectures applicable for all three degrees of freedom Z, Rx and Ry. Unless the context otherwise requires, signals such as *ls*, *ls'*, *Zif*, etc., include data of those three degrees of freedom.

The transfer function H_ls of the level sensor LS is not ideal. If an ideal level sensor ILS is notionally introduced into the system then the various possible errors in the complete system can be identified. Since the ideal level sensor cannot be built, it and the errors derived by reference to it are shown in phantom in Figure 3. These errors are the level sensor error *lse*, dynamic measurement error *dme* and dynamic leveling error *dle*. Thus the errors in the leveling system may be defined as:

lse = wafer . H_ils – wafer . H_ls .... **(1)**

dme = wafer . H_ils – wafer . H_ls . H_wsf .... **(2)**

vse = wafer . H_ls . H_wsf– wafer . H_ls . H_wsf . H_sv .... **(3)**

dle = wafer . H_ils – wafer . H_ls . H_wsf . H_sv .... **(4)**

hse = wafer . H_ls . H_wsf . H_sh .... **(5)**

where H_aa is the transfer function of element AA in the control system. These various transfer functions will in general be functions of Z, Rx and Ry and may include terms representing crosstalk into other degrees of freedom. Of these errors, the first four are defined for Z, Rx, Ry and Ztotal, the last only for X and Y. Ztotal is a combination of Z, Rx and Ry errors in such a way that it represents the maximal Z displacement in the radiation system's exposure slit, effectively the maximum Z error on one of the four corners of the slit. Ztotal is calculated as $Z \pm Rx.slitsize_y/2 \pm Ry.slitsize_x/2$.

The transfer function H_wsf of the wafershape filter is determined for each application to provided the desired improvements to the above errors. For example, the transfer function H_wsf may be empirically derived to compensate for the divergence of the transfer function H_ls of the actual level sensor LS and so reduce the dynamic measurement error *dme* to zero. The ideal level sensor transfer function has a magnitude that decreases with spatial frequency, and a first zero-crossing at a spatial frequency equal to the inverse of the width of the exposure slit in the scan direction (in the case of a step-and-scan apparatus). This is advantageous as it prevents the wafer stage attempting to follow variations in the wafer

surface of wavelength shorter than the slit width and in particular reduces undesired horizontal movements due to high frequency cross-talk.

The wafershape filter transfer function can also be adjusted to compensate for or compromise between the other errors. Appropriate forms for the wafershape filter transfer function to achieve the desired effects can be derived empirically or by modeling the servo system. For example, in one servo system it was determined that Y errors were out of specification whilst Ztotal and Rx errors were comfortably with limits. A notch filter in the Rx wafer shape transfer function with a center frequency equal to the peak frequency of the Y moving average error was found to improve Y accuracy at an acceptable cost to Rx and Ztotal. The damping coefficients were selected to provide the desired improvement in Y whilst reducing the cost to Rx and Ztotal.

Embodiment 2

In a second embodiment, shown in Figure 5, the control system makes use of information indicating the position of the wafer table WT provided by an interferometric displacement measurement system IF. Suitable three, five and six-axis interferometric metrology systems are described in WO99/28790 (P-0077) and WO99/32940 (P-0079), for example. An LVDT measurement system may also be used in place of the interferometer. In such a system, three LVDTs are located under the wafer table WT and their outputs transformed to give Z, Rx and Ry data. As shown in Figure 4, the interferometer system IF measures the position Zif of the wafer table WT (sometimes referred to as the mirror block, as the interferometer system makes use of mirrors bonded to the sides of the wafer table) relative to the focal plane FP of the projection lens system PL whilst the level sensor measures the height ls of the upper surface of the wafer W. (Note that whilst the ls and Zif measurements are shown spaced apart in Figure 4 for clarity, in fact the interferometer and level sensor should be arranged to make measurements at the same position in the XY plane.) The interferometer data, though denoted simply Zif, includes information regarding the horizontal tilt, Rx and Ry, of the wafer table as well as vertical position, Z. By subtracting the level sensor data from the interferometer data, a value for the wafershape ws is obtained, i.e.:

$$ws = Zif - ls \qquad \textbf{(6)}$$

The control system using the interferometer data is shown in Figure 5. The control strategy for this system is that the wafershape filter WSF provides the filtered wafershape signal ws' which acts as setpoint data for an inner closed-loop control system (within the double dotted line in Figure 5) comprising controller CONT, the short-stroke table drive system MECH, the

interferometer IF and a subtractor which subtracts the position of the wafer table as indicated by the interferometer data *Zif* from the filtered wafershape data *ws'*. In the second embodiment, the wafer shape filter WSF acts on the wafershape data *ws* (which represents the actual shape of the wafer) rather than the level sensor data (which includes the instantaneous position of the wafer table). The inner loop has a high bandwidth, e.g. 50 or 100 Hz or more, and is able to follow the wafershape setpoint *ws'* accurately. The outer loop determines the setpoint by filtering the wafershape signal *ws*. The wafershape filter WFS will therefore not affect the performance of the inner loop. The outer loop needs to be stable and to have limited closed loop amplification.

As in the first embodiment, the wafershape filter is selected to correct measurement errors in the level sensor LS and to reduce vertical (tilt) to horizontal cross-over.

Embodiment 3

A third embodiment of the invention is described with reference to Figures 6 and 7. The third embodiment incorporates so-called "look-ahead" in the level sensor LS to compensate for delay which is caused in the wafershape filter. The level sensor including look-ahead is denoted LS' and utilizes a measurement spot pattern as depicted in Figure 6. Measurement spots P1 and Q2 are positioned ahead of the center of the projection lens whilst Q1 and P2 are behind. With this layout, sensor look-ahead for Z and Ry position is effected by weighting the advance spot measurements more heavily than the back spots. (Note that sensor look-ahead is not used in Rx because Rx measurements require both advance and back spot measurements.) Without sensor look-ahead, center level sensor Z, Rx and Ry signals are calculated as follows:

$$ls\_cent_Z = (Z_{P1} + Z_{P2} + Z_{Q1} + Z_{Q2})/4 \quad \textbf{(7)}$$

$$ls\_cent_{Rx} = ((Z_{P1} + Z_{Q2})/2 - (Z_{P2} + Z_{Q1})/2)/arm\_y \quad \textbf{(8)}$$

$$ls\_cent_{Ry} = ((Z_{P1} + Z_{Q1})/2 - (Z_{P2} + Z_{Q2})/2)/arm\_x \quad \textbf{(9)}$$

To calculate look-ahead in Z and Ry, gradient values are defined as follows:

$$ls\_grad_Z = dz/dy = ls\_cent_{Rx} \quad \textbf{(10)}$$

$$ls\_grad_{Rx} = 0 \quad \textbf{(11)}$$

$$ls\_grad_{Ry} = dRy/dy = ((Z_{P1} - Z_{Q2})/arm\_x - (Z_{Q1} - Z_{P2})/arm\_x))/arm\_y \quad \textbf{(12)}$$

The look-ahead level sensor readings are then:

$$ls\_front_Z = ls\_cent_Z + y\_l\_az \, . \, ls\_grad_Z \quad \textbf{(13)}$$

$$ls\_front_{Rx} = ls\_cent_{Rx} \quad \text{(14)}$$

$$ls\_front_{Ry} = ls\_cent_{Ry} + y\_l\_a_{Ry} \, . \, ls\_grad_{Ry} \quad \text{(15)}$$

where y_l_a is the look-ahead distance which can be different for Z and Ry.

The control system, shown in Figure 7, is then essentially the same as that of the second embodiment, shown in Figure 5, save that the level sensor LS' is adapted to provide the gradient signals, and a look-ahead amplifier y_l_a and adder are introduced to generate the sensor look-ahead data.

Embodiment 4

The fourth embodiment, which is shown in Figure 8, is similar to the third but includes look-ahead in the interferometer IF, or LVDT measurement system, as well. This avoids errors in ls_front_Z which may occur in the third embodiment when there is a significant Rx tilt. In the third embodiment, the Z level sensor front signal and the Z interferometer signal are not measured at exactly the same spot so that there will be an error in the Z wafershape signal ws if there is a significant Rx tilt. Accordingly, an interferometer gradient is defined for the Z signal, as follows:

$$ifm\_grad_Z = ifm\_cent_{Rx} \quad \text{(16)}$$

The forward-measured interferometer Z signal is then:

$$ifm\_front_Z = ifm\_cent_Z + y\_l\_a_Z \, . \, ifm\_grad_Z \quad \text{(17)}$$

Note that the interferometer gradients for Rx and Ry are defined as zero so that the corresponding look-ahead signals are equal to the center signals.

The resulting control system architecture is shown in Figure 8; it corresponds to that of the third embodiment save for the additional amplifier and adder to generate the *if_front* signals.

Embodiment 5

The control system architecture of a fifth embodiment of the invention is shown in Figure 9. This arrangement is effectively the same as the fourth embodiment but, by subtracting the center and gradient signals before multiplication by y_l_a, one multiplier is saved.

Embodiment 6

A sixth embodiment of the invention is shown in Figure 10. The sixth embodiment incorporates an additional correction AF_corr to compensate for changes in the position of the actual best focal plane. Such changes may be effected deliberately or may be caused by temperature variations in the elements of the projection optical system PL and temperature or pressure variation in the gas or air filling the projection optical system PL. A measured or predicted change of the actual focal plane in Z or Ry is automatically compensated for in the level sensor LS' which measures the position of the wafer surface relative to the optimum focal plane. However, a change of the optimum focal plane in Rx will, with sensor look-ahead, result in an error in the Z position of the wafer surface. To prevent this, the wafershape Z value is corrected by $-\Delta Rx . y\_l\_a$, where ΔRx is the change in the position of the optimum focal plane, or the Z gradient is corrected by $-\Delta Rx$. The latter alternative is effected in the sixth embodiment in which AF_corr is subtracted from the differential gradient signal $if\_grad - ls\_grad$. AF_corr is defined as ΔRx for Z and zero for Rx and Ry.

Examples

To demonstrate the effectiveness of the present invention the servo architecture of the sixth embodiment was used with a 4^{th} order wafershape filter comprising two 2^{nd} order notch filters. The filter and look-ahead settings for Z, Rx and Ry for two examples, Example 1 and Example 2, are shown in Figure 15. In Figure 15, "nu" indicates "not used" and "na" indicates "not available".

In Example 1, no Rx wafershape filter was used and the wafershape filter acts on a time series of values representing heights at positions spaced in the Y (scanning) direction. However in Example 2, an Rx filter was added to the filter of example 1 to improve the Y performance at the expense of Rx performance. Simulations were carried out using test data derived from a sample of six test wafers. In the simulations, moving averages (MA) and moving standard deviations (MSD) for servo errors in Ztotal, Z, Rz, Ry, X and Y, as well as dynamic leveling errors in Ztotal, Z, Rx and Ry, were calculated, i.e. a total of 120 values. As compared to leveling without any wafershape filtering, Example 1 reduced the number of out-of-spec results from 20 to 11 whilst Example 2 reduced this to 1.

The wafershape filter settings of Examples 1 and 2 are based on a scanning speed of 250mm/s. For other scanning speeds, the look-ahead distances and filters can be adapted, e.g. so as to maintain a constant look-ahead time, rather than distance. Similarly, the frequency

values of the wafershape filter can be made proportional to scanning speed so that they represent constant spatial frequencies.

The effectiveness of the present invention is further demonstrated by Figures 11 to 14 which show test results obtained using the filter of Example 1 and a test wafer with a special (waved) step topology. In the negative X half of the wafer the surface has a step topology with decreasing wavelength in the Y direction. The positive X half is flat. Figures 11A and 11B show actual Z position movements (dashed) on this wafer compared to ideal (solid), without and with wafershape filtering respectively. Figures 12A and 12B show actual Ry movements (dashed) compared to ideal (solid), without and with wafershape filtering respectively. Figures 13A and 13B show actual Z level sensor transfer functions (dashed) compared to ideal (solid), without and with wafershape filtering respectively. Figures 14A and 14B show actual Ry level sensor transfer functions (dashed) compared to ideal (solid), without and with wafershape filtering respectively. It can readily be seen that with the invention the transfer functions and wafer movements are considerably closer to the ideal. In particular, undesirable high frequency movements of the wafer table are avoided.

As mentioned above, the actual form of the filter will be determined according to the specific embodiment of the invention and the desired performance criteria. One approach to selection of a suitable filter is to first find a level sensor look-ahead distance which ensures that the look-ahead transfer function of the level sensor lies above the ideal transfer function, at least up to the first zero-crossing at $1/slitsize_Y$. Using a two-notch filter, the first notch is then used to shape the transfer function up to the first zero-crossing. The second notch is used to filter off the frequencies higher than the first zero-crossing and to adjust the phase of the transfer function upto the first zero-crossing.

Whilst we have described above specific embodiments of the invention it will be appreciated that the invention may be practiced otherwise than as described. The description is not intended to limit the invention. It should be explicitly noted that the current invention can be applied to substrate leveling alone, to mask leveling alone, or to a combination of substrate leveling and mask leveling.

CLAIMS

1. A lithographic projection apparatus comprising:

a radiation system for supplying a projection beam of radiation;

a first object table provided with a first object holder for holding a mask;

a second object table provided with a second object holder for holding a substrate;

a projection system for imaging an irradiated portion of the mask onto a target portion of the substrate;

a level sensor for measuring at least one of the vertical position and tilt about at least one horizontal axis of an object held by one of said object holders, and generating a position signal; and

a servo system responsive to said position signal for moving said object to a desired position; characterized by:

a filter connected between said level sensor and said servo system for filtering said position signal.

2. Apparatus according to claim 1 wherein the filtered position signal forms a setpoint for said servo system.

3. Apparatus according to claim 2 wherein said filter is a low pass filter arranged to pass components of said position signal having a spatial frequency lower that a predetermined spatial frequency.

4. Apparatus according to claim 3 wherein said first and second object tables are moveable to effect a scanning exposure of a substrate held in said second object holder, and said predetermined spatial frequency is substantially equal to 1 divided by the width of said projection beam in the scanning direction of the apparatus.

5. Apparatus according to claim 1, 2, 3 or 4 wherein said filter is adapted to reduce crosstalk between rotation of said object about a horizontal axis and horizontal translations of said object.

6. Apparatus according to any one of the preceding claims further comprising a position sensor for detecting the position of said object table, the output of said position sensor being

subtracted from the output of said level sensor to form said position signal; and wherein said servo system comprises an inner control loop including said position sensor for controlling the position of said object table, and said filtered position signal forms a setpoint for said inner control loop.

7. Apparatus according to claim 6 wherein said position sensor comprises an interferometric displacement measuring system or a Linear Variable Differential Transformer (LVDT) measuring system.

8. Apparatus according to any one of the preceding claims wherein said first and second object tables are moveable to effect a scanning exposure of a substrate held in said second object holder, and said level sensor is arranged to measure at least one of the vertical position and the tilt about at least one horizontal axis of a measurement point on said object ahead of the center of said projection beam in the scanning direction.

9. Apparatus according to claim 8 when dependent on claim 6 or 7 wherein said position sensor is arranged to measure the position of said object table at a point corresponding to said measurement point of said level sensor.

10. Apparatus according to claim 8 or 9 wherein the distance of said measurement point ahead of said center of said projection beam is dependent on the speed of said scanning exposure.

11. Apparatus according to claim 8, 9 or 10 wherein said filter has a transfer function that is dependent on the speed of said scanning exposure.

12. Apparatus according to any one of the preceding claims wherein said object table is said second object table and said object is said substrate.

13. A method of manufacturing a device using a lithographic projection apparatus comprising:

a radiation system for supplying a projection beam of radiation;

a first object table provided with a mask holder for holding a mask;

a second object table provided with a substrate holder for holding a substrate;

a level sensor for measuring at least one of the vertical position and tilt about at least one horizontal axis of an object held by one of said object holders, and generating a position signal; and

a servo system responsive to said position signal for moving said object to a desired position; the method comprising the steps of:

providing a mask bearing a pattern to said first object table;

providing a substrate having a radiation-sensitive layer to said second object table; and

imaging said irradiated portions of the mask onto said target portions of the substrate whilst operating said servo system to maintain said object at said desired position;

characterized by the step of:

filtering said position signal before it is used by said servo system to control the position of said object.

14. A device manufactured according to the method of claim 13

ABSTRACT

Leveling Control in Lithographic Projection Apparatus

On-the-Fly leveling in a lithographic apparatus is conducted using a setpoint derived by filtering the output of the combination of the output of a level sensor and another position sensor (LVDT or IFM). The level sensor may include look-ahead. The filter may be a low pass filter to cut-off level variations of wavelength shorter than the width of the slit during a scanning exposure. The filter may also be selected to reduce cross-talk between tilt movements and horizontal displacements.

Fig. 3

Fig. 1

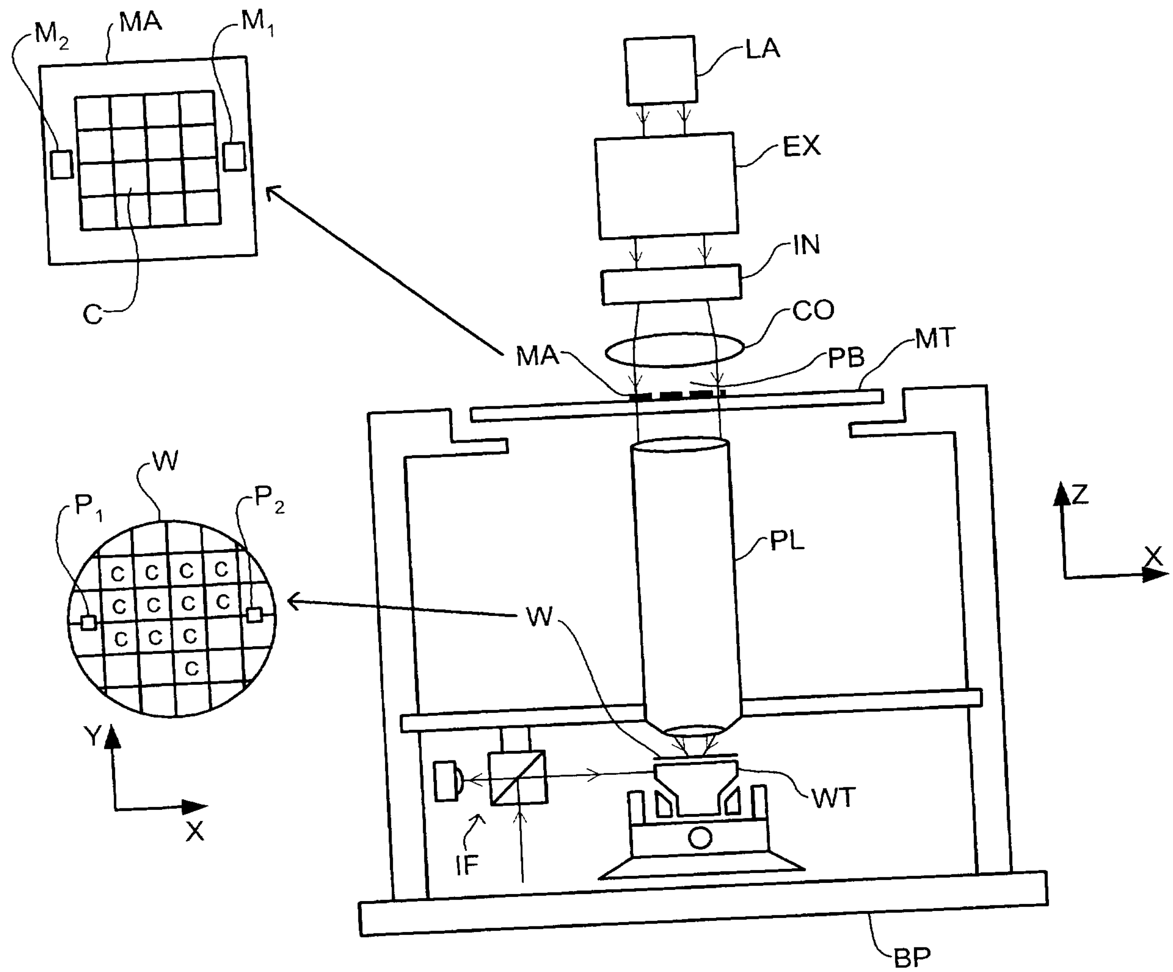

FIG. 2

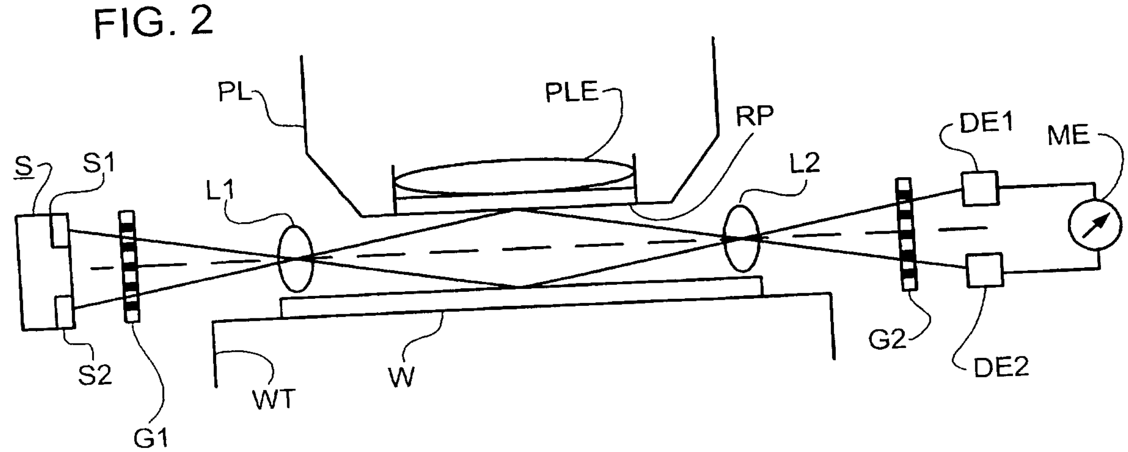

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FIG. 3

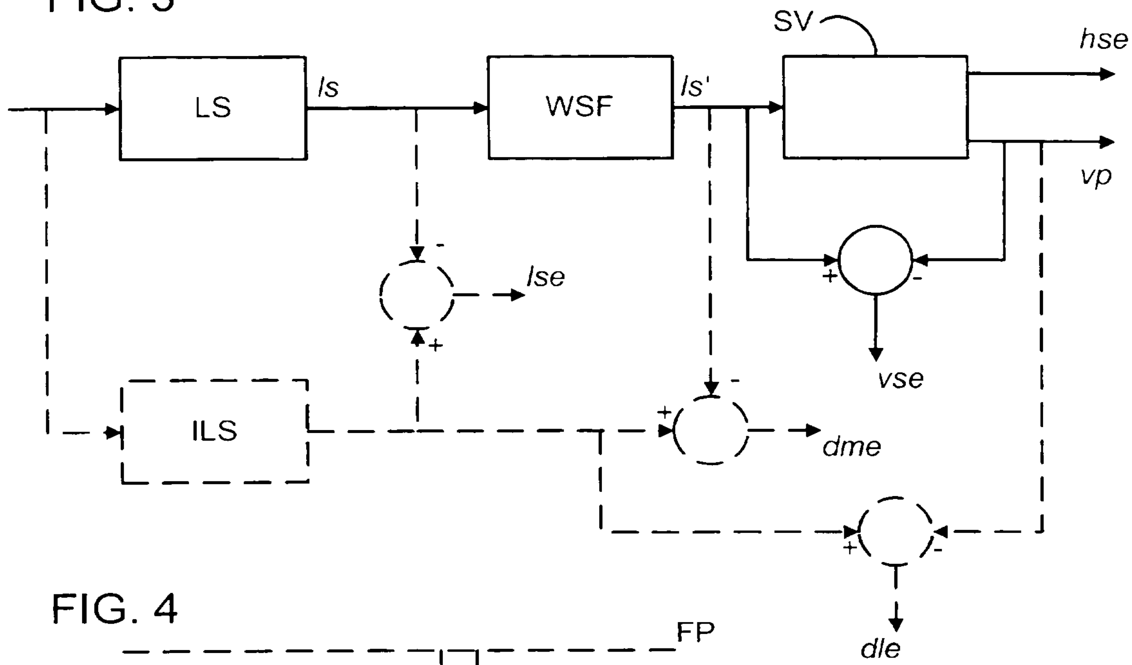

FIG. 4

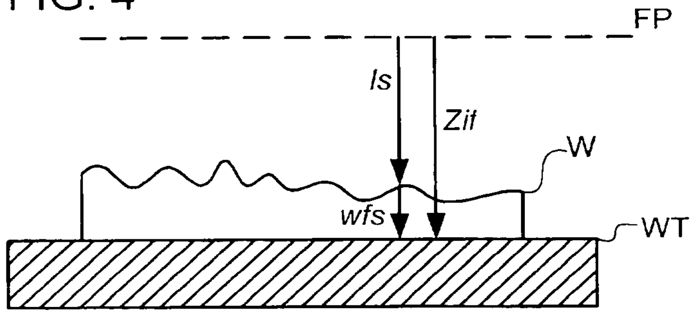

FIG. 5

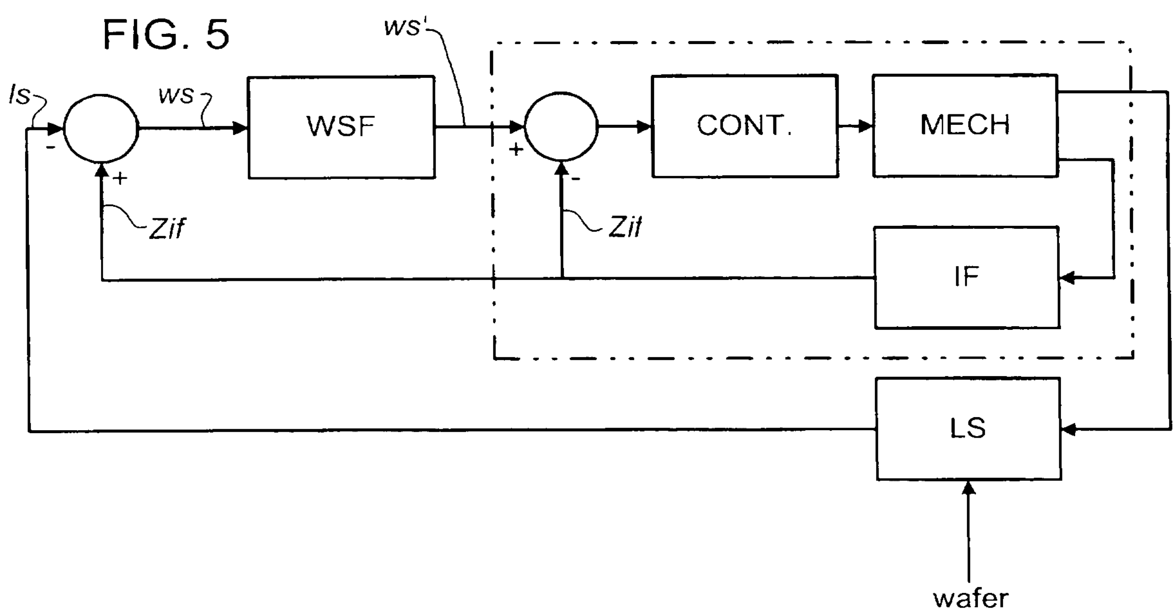

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Fig. 6

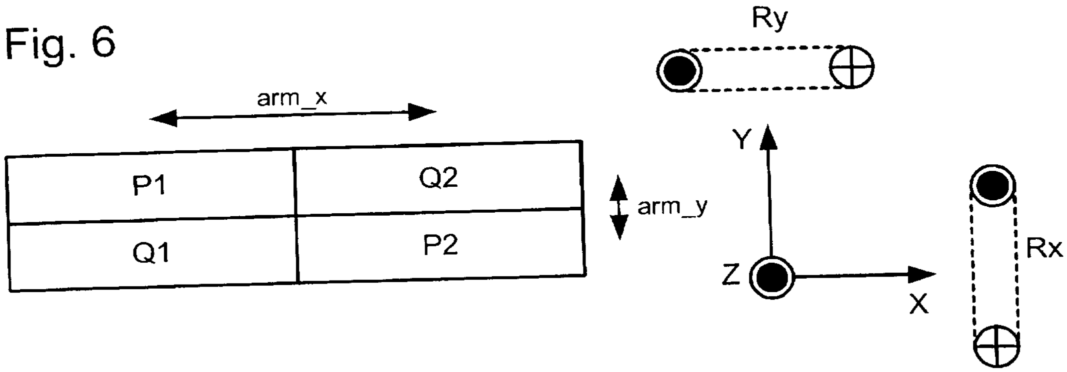

FIG. 7

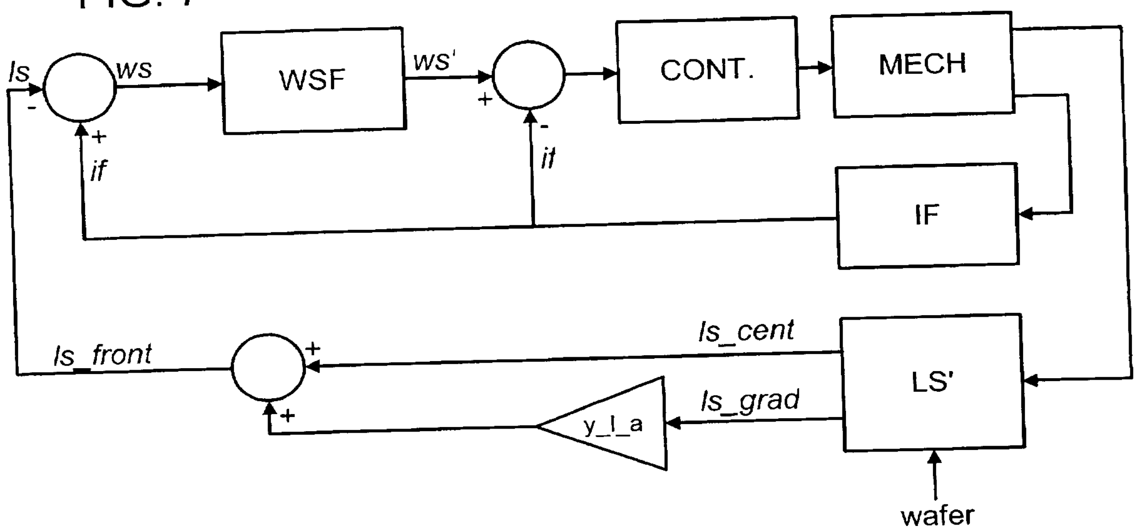

FIG. 8

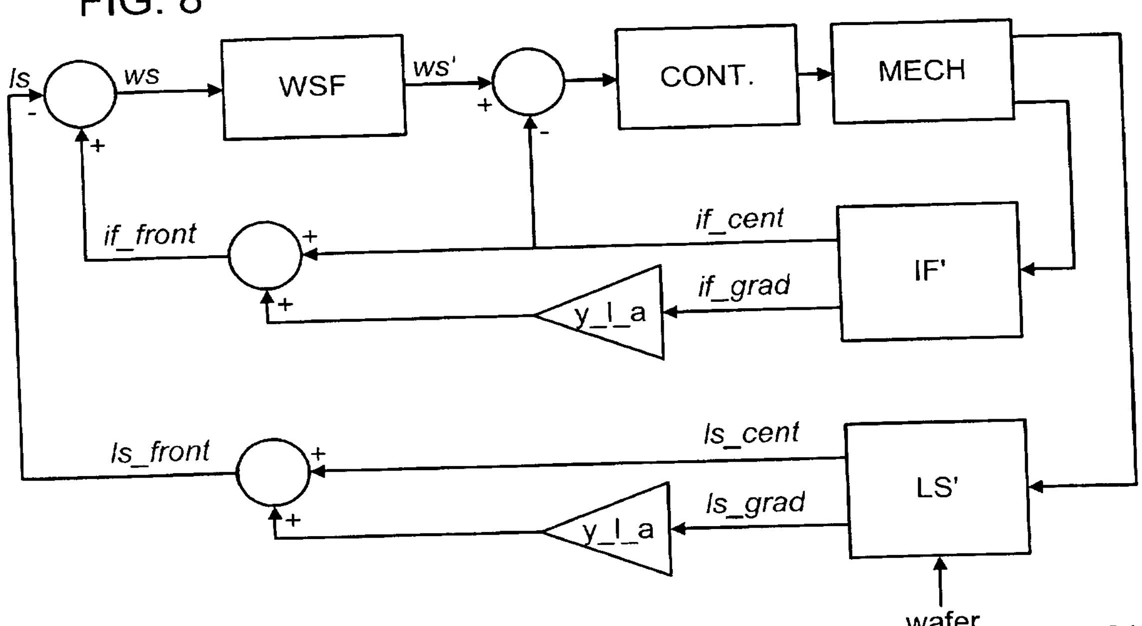

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FIG. 9

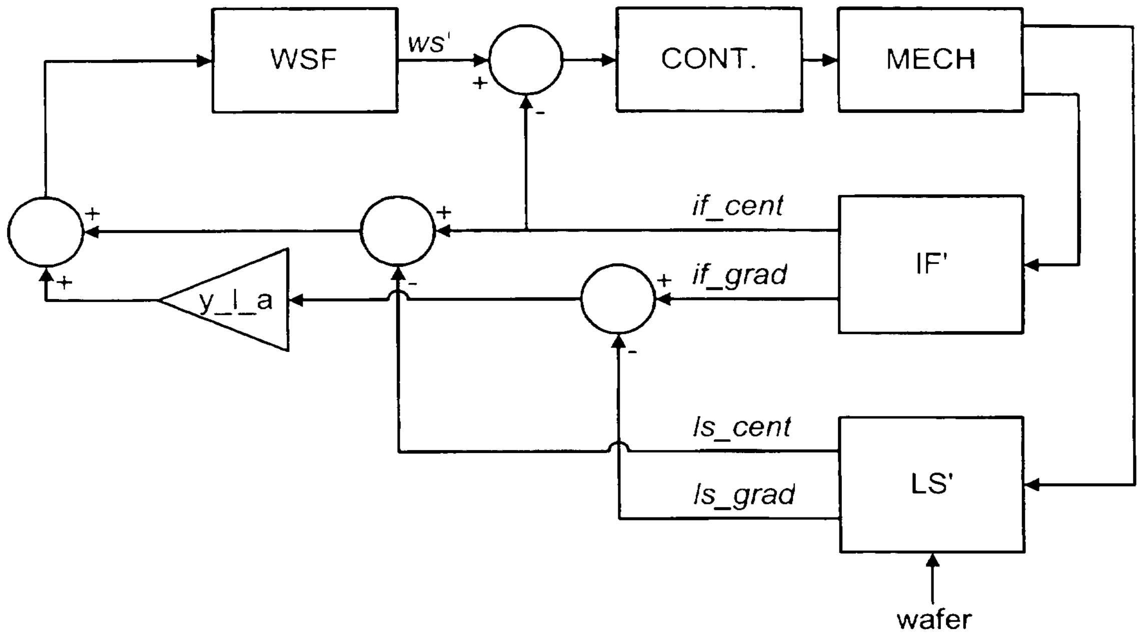

FIG. 10

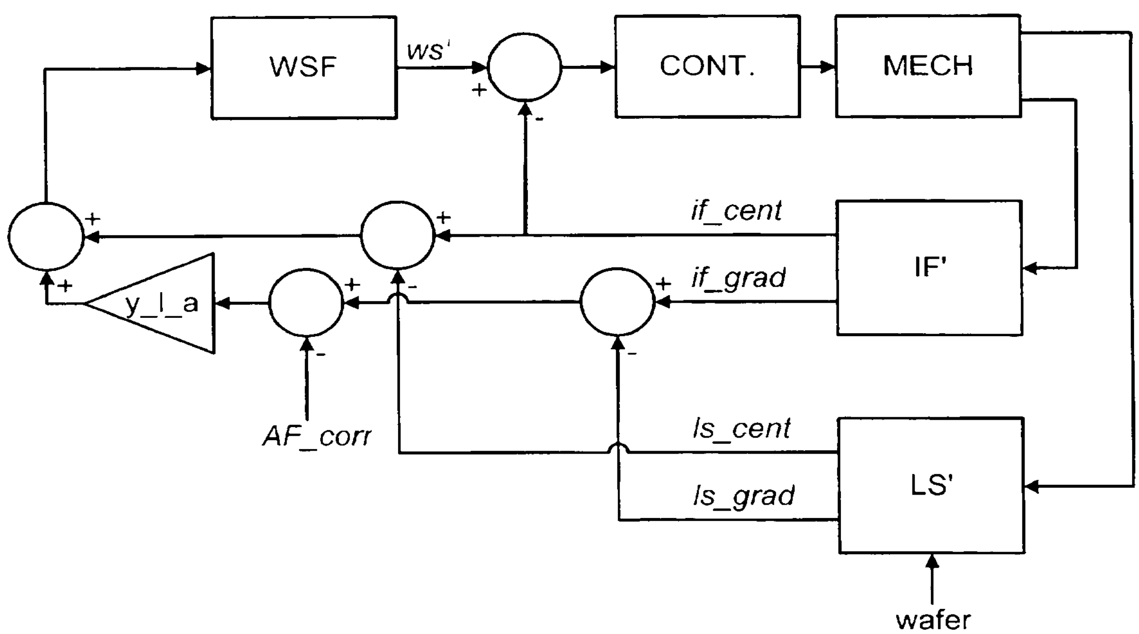

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FIG. 11A

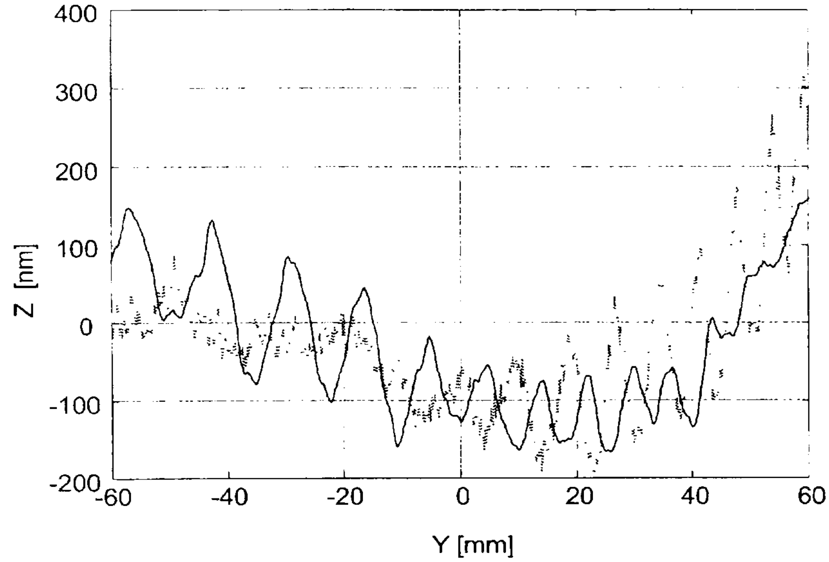

FIG. 11B

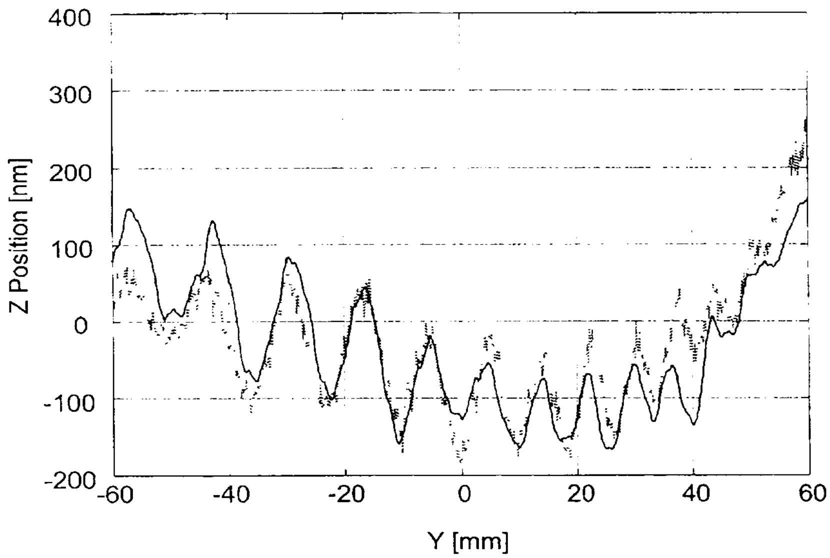

FIG. 12A

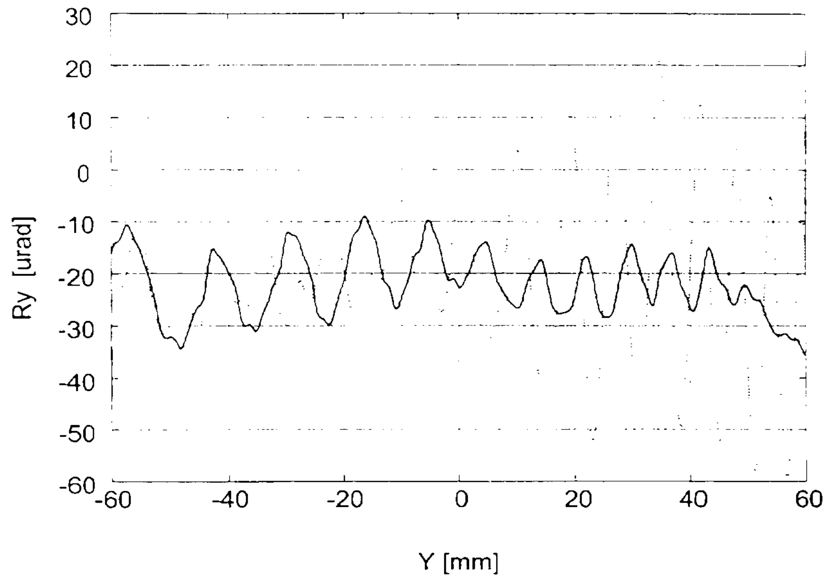

FIG. 12B

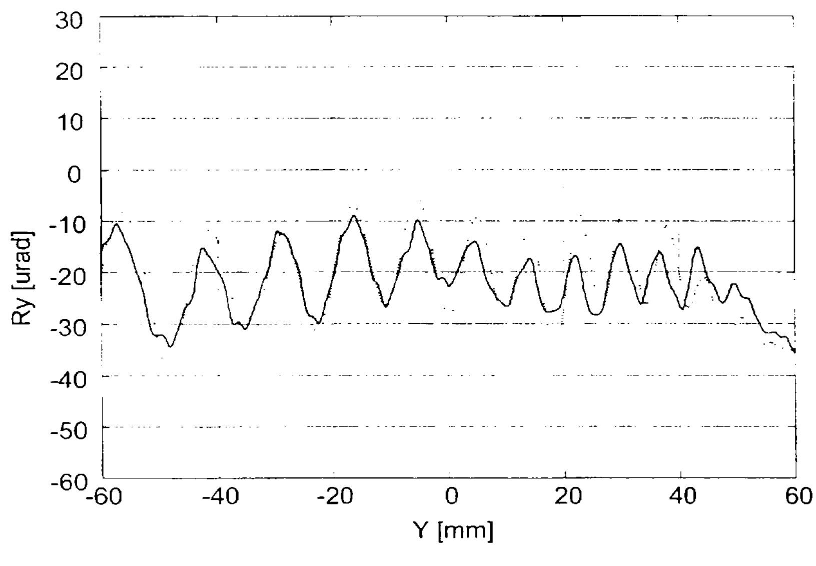

FIG. 13A

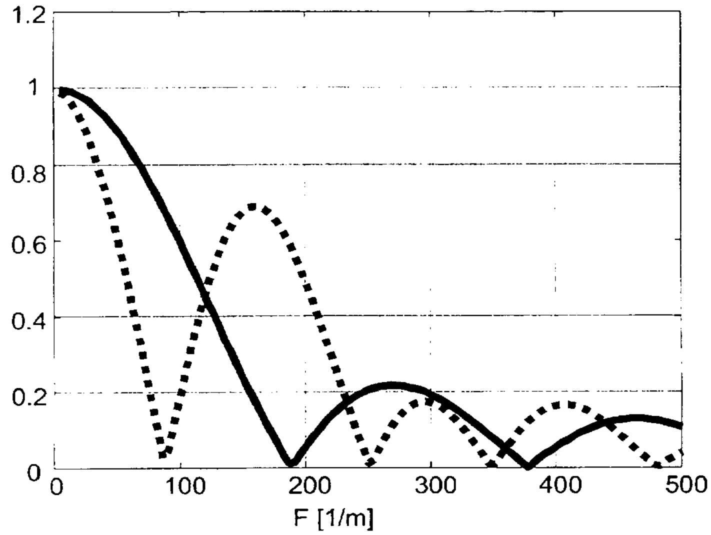

FIG. 13B

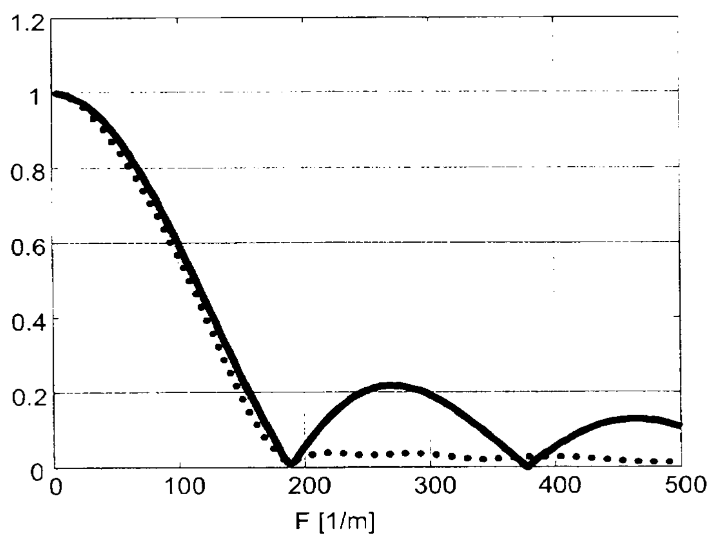

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FIG. 14A

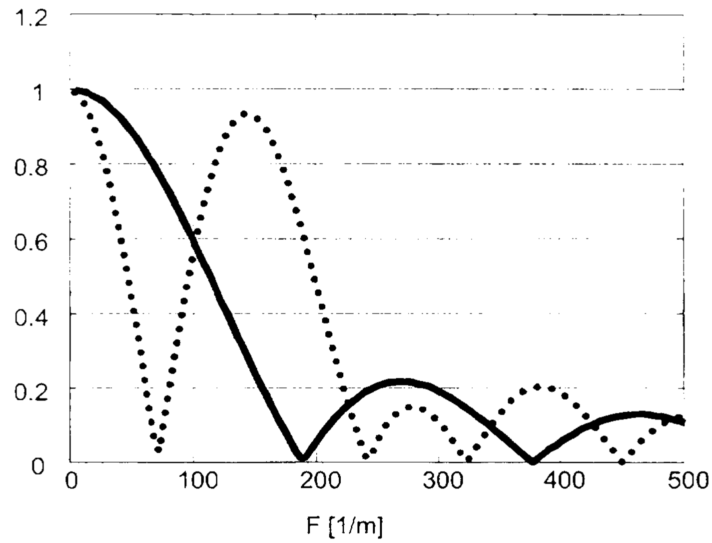

FIG. 14B

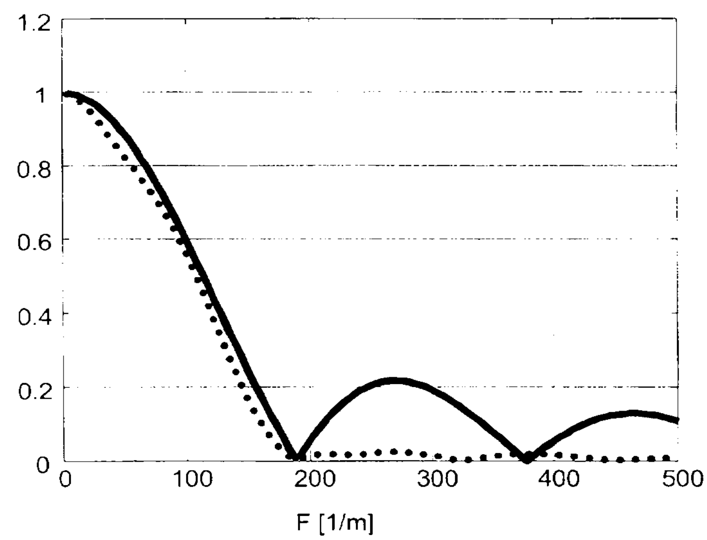

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FIG. 15

		Example 1			Example 2		
Z							
y_l_a		2.8 mm			2.8 mm		
wfs		notch 1	notch 2	notch 3	notch 1	notch 2	notch 3
	zero f [Hz]	47	1000	nu	47	1000	nu
	zero damp	0.01	0.1		0.01	0.1	
	pole f [Hz]	40	50		40	50	
	pole damp	0.8	0.7		0.8	0.7	
Ry							
y_l_a		3.5 mm			3.5 mm		
wfs		notch 1	notch 2	notch 3	notch 1	notch 2	notch 3
	zero f [Hz]	47	1000	nu	47	1000	nu
	zero damp	0.01	0.1		0.01	0.1	
	pole f [Hz]	35	50		35	50	
	pole damp	1	0.7		1	0.7	
Rx							
y_l_a		na			na		
wfs		notch 1	notch 2	notch 3	notch 1	notch 2	notch 3
	zero f [Hz]	nu	nu	nu	30		
	zero damp				0.1		
	pole f [Hz]				30		
	pole damp				0.55		

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